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Description

Method and control device for operating a mill train for metal strip

The invention relates to a method according to the preamble of claim 1; one application is particularly suitable for operation in a hot-rolling mill, e.g. in the finishing train, but is not restricted to this.

The invention also relates to a control device according to the preamble of claim 10.

It is known from the unexamined German application DE 198 51 554 A1 that the profile and/or flatness of a metal strip is determined at the discharge point of a mill train and is used to preset a mill train. The measured visible flatness is supplied here to a neural network in the form of input parameters.

The object of the invention is to operate a mill train for metal strip such that a control is provided to ensure that a required visible flatness of the rolled metal strip is complied with in a reliable and sufficiently accurate manner within predefined limits.

The object is achieved by a method of the type mentioned above, with the visible flatness and an intrinsic flatness of the metal strip being taken into account using a bulge model when controlling the roll stands.

The claimed possibility of taking into account both the visible flatness of the mill train and the intrinsic flatness with the aid of the bulge model means that extremely stringent requirements can be complied with in respect of the quality of the visible flatness of the metal strip, even though the visible flatness or waviness of the metal strip sometimes completely disappears during rolling under tension, i.e. between the roll posts, and cannot therefore be measured in practice in many instances within the mill train.

The bulge model is used first to establish a unique relationship between the intrinsic and visible flatness of the metal strip. It is then possible for the first time not just to carry out presettings on the basis of flatness measurements but also to use the visible flatness for accurate control or regulation of the ongoing rolling process.

The visible flatness is advantageously determined in the form of a bulge pattern. The bulge pattern is easy to compare in respect of data and can be stored with relatively little outlay.

The bulge pattern is advantageously three-dimensional.

At least one of the variables wavelength, amplitude and phase offset of the individual tracks is advantageously evaluated in addition to the relative length of individual tracks of the metal strip to determine the bulge pattern of the metal strip. The bulge pattern can thus be identified much more accurately.

A multi-track laser measuring device is advantageously used to determine the bulge pattern, allowing economical identification

of the bulge pattern with a sufficiently high level of precision.

The visible flatness is advantageously measured topometrically. This makes surface identification of the surface structure of the strip and in particular of the bulge pattern directly possible.

The bulge model is advantageously used to translate values for the visible flatness into values for the intrinsic flatness or values for the intrinsic flatness into values for the visible flatness. This allows intrinsic strip flatness values calculated using a material flow model and visible strip flatness values measured at the discharge point of a mill train to be brought into line with each other or verified.

The flatness values are advantageously translated online. This allows particularly precise control or regulation of the strip flatness.

The flatness values are advantageously translated with the aid of an on-line-capable approximation function. This can save on-line computing time during the translation between visible and intrinsic flatness.

The bulge pattern of the metal strip is advantageously modeled using the bulge model by applying a fictitious temperature distribution in the transverse direction of the metal strip based on the intrinsic flatness of the metal strip. The thermal expansion in the longitudinal direction of the strip, but not however in the transverse direction, corresponding to this strip temperature distribution corresponds to a length

distribution that can be assigned to the intrinsic flatness. Only one segment of limited length must therefore be modeled and the model equations for elastic plate deformations with major deflections can be worked out with suitable edge conditions at the segment edges.

A material flow model is advantageously used to determine an intrinsic flatness of the metal strip - looked at in the material flow direction - before a physical point for measuring flatness.

One or more flatness limit values are advantageously predefined at freely selectable points within and/or after the mill train in order to control the mill train. The flatness limit values can relate to the intrinsic flatness and/or the visible flatness. Because flatness limit values can be predefined everywhere within or after the mill train, regulation accuracies for the rolling process can be significantly increased.

The object is also achieved by a control device for operating a mill train for metal strip with at least one roll stand, in particular according to the method described above, with the control device having at least one regulating unit coupled to a bulge model. Advantageous embodiments of the control device are specified in the subclaims. The advantages of the control device are similar to those of the method.

Further advantages and details will emerge from the description which follows of an exemplary embodiment in conjunction with the figures, in which:

FIG 1 shows a multi-stand mill train for rolling metal strip and a control device assigned to the mill train,

FIGs 2a-2c show examples of metal strip with flatness errors,

FIG 3 shows the division of a metal strip into tracks,

FIG 4 shows a section of a multi-stand mill train with a control device,

FIG 5 shows the geometry of a section of a metal strip.

According to Figure 1 a mill train for rolling a metal strip 1 is controlled by a control processor 2. The metal strip 1 can for example be a steel strip, an aluminum strip or a non-ferrous metal strip, in particular a copper strip. The mill train has at least two roll stands 3

The roll stands 3 have at least working rolls 4 and - as shown in Figure 1 for one of the roll stands 3 - generally also back-up rolls 5. The roll stands 3 could have even more rolls, for example intermediate rolls that can be displaced axially.

The metal strip 1 passes through the mill train in its longitudinal direction x, with the transverse direction y of the metal strip being largely parallel to the axes of the working rolls 4.

The mill train shown in Figure 1 is configured as a finishing train for hot-rolling steel strip. The present invention is

particularly suitable for use with a multi-stand finishing train for hot-rolling steel strip but is not restricted to this. The mill train could in particular also be configured as a cold-rolling mill train (tandem train) and/or for rolling a non-ferrous metal (e.g. aluminum, copper or another non-ferrous metal).

The control device 2 has a regulating unit 11. This in turn has a module 10 for profile and flatness control, which is coupled to a material flow model 9. The control device 2 predefines target values for profile and flatness control elements (not shown here) to the stand regulators 6. The stand regulators 6 then adjust the control elements according to the predefined target values.

The input variables supplied to the control device 2 include for example pass schedule data such as the input thickness of the metal strip 1 and a roll force and draft reduction per pass for each roll stand 3. The input variables generally also include an end thickness, a target profile value, a target thickness contour and a target flatness pattern of the metal strip 1 at the discharge point of the mill train. The rolled metal strip 1 should generally be as flat as possible.

However the metal strip 1 often has flatness errors, as shown by way of an example and schematically in Figures 2a, 2b and 2c. Flatness errors of the metal strip 1 can be measured at one point x2, as shown in Figure 1, for example using a multi-track laser measuring device 13.

Figure 2a shows a centric bulge in the metal strip 1. Figure 2b shows flatness errors at the edges of the metal strip 1. Figure

2c shows bulges in the metal strip 1, which occur repeatedly in the longitudinal direction x of the metal strip 1 and in two areas in particular in the transverse direction y of the metal strip 1.

The bulges in the metal strip 1 are caused in particular by internal stresses in the metal strip 1. Internal stresses in the metal strip are also referred to as intrinsic strip flatness ip.

Figure 3 shows the division of a metal strip 1 into fictitious tracks S1 to Sn or into measuring tracks S1′ to Sm′. If the metal strip 1 were to be cut up into narrow longitudinal strips or into tracks S1 to Sn, it would be possible to measure an uneven strip length distribution (the intrinsic strip length distribution), which is the cause of the internal stresses in the metal strip 1. The multi-track laser measuring device 13 captures the relative length of the metal strip 1 for each measuring track S1′ to Sm′ and preferably also determines variables such as wavelength, amplitude and/or the phase offset of the individual tracks S1′ to Sm′. It is important that the associated intrinsic or measured relative lengths do not correspond for corresponding fictitious tracks S1 to Sn and measuring tracks S1′ to Sm′.

As shown in Figure 4, a distinction is made between intrinsic strip flatness ip and visible strip flatness vp when hot-rolling metal strip 1. The intrinsic strip flatness ip refers, as mentioned above, to the strip length distribution over the tracks S1 to Sn. The visible flatness vp results from the bulge behavior of the strip, which is for example a function of variables such as strip thickness, strip width, the elasticity

module of the metal strip 1 and the overall tension to which the metal strip 1 is subjected.

According to Figure 4 the visible flatness vp is measured at one point x2 at the discharge point of the mill train, in particular a finishing train, and supplied to a bulge model 12. The visible flatness vp is measured according to the invention such that not only is the visible strip length distribution over the strip width in the transverse direction y an output variable of a measuring device but the three-dimensional bulge pattern of the strip can also be reconstructed from the measuring device output variables. In the case of a multi-track laser measuring system therefore not only the (relative) length of the individual measuring tracks S1′ to Sm′ is output by the measuring device but also wavelength and phase offset for each track S1′ to Sm′. With a topometric measurement of the visible flatness vp the surface structure of the metal strip 1 is captured at the surface and three-dimensionally over large areas of the metal strip 1. A topometric strip flatness measurement is preferably based on a strip projection method. Strip patterns are thereby projected onto the surface of the metal strip 1 and continuously captured with the aid of a matrix camera.

The intrinsic flatness ip is preferably calculated at a point x1 between or after the roll stands 3, in particular between and/or after the roll stands 3 of a finishing train. The calculation is thereby preferably made using a material flow model 9 (see Figure 1), which is preferably part of a regulating unit 11. The intrinsic flatness ip calculated by the material flow model 9 can be compared with the measured visible flatness vp with the aid of the bulge model 12 at one point x2

at the discharge point of the mill train, at which the visible flatness vp is measured. In the case of a cold-rolling mill in particular it would essentially also be possible to measure the intrinsic flatness ip on the metal strip 1.

The bulge model 12 allows a unique relationship to be established between intrinsic flatness ip and visible flatness vp, as far as possible. Thus for example with a very thick metal strip 1 with moderate intrinsic lack of flatness it is not possible to conclude the intrinsic flatness ip from the bulge behavior, as such a metal strip 1 generally does not bulge.

The various flatness values (ip and vp) are preferably determined in the following sequence:

1. The visible flatness vp, which generally corresponds to the bulge behavior of the metal strip 1, is generally measured after a last roll stand 3, for example at the discharge point of a finishing train.

2. The bulge model 12 is used to determine the intrinsic flatness ip of the metal strip 1 at the point for measuring the visible flatness vp (see step 1).

3. The material flow model 9 is used to determine the intrinsic flatness ip between the roll stands 3, for example within the finishing train. The intrinsic flatness can therefore be determined before the physical point for measuring flatness, in this instance intrinsic flatness, looked at in the material flow direction.

The relationship between an intrinsic flatness ip between the roll stands 3 and an intrinsic flatness ip after the last of the roll stands 3 is established using the material flow model 9. Input variables such as the strip thickness contours of the metal strip 1 as well as flatness patterns or flatness values before and after passage through a roll stand 3 can be supplied to the material flow model 9. The material flow model 9 determines the intrinsic flatness pattern of the metal strip 1 online after passage through the roll stand 3 as well as a roll force pattern in the transverse direction y of the metal strip 1 and supplies it to a roll deformation model (not shown in more detail here). The roll deformation model (not shown in more detail here) is preferably part of a regulating unit 11. The roll deformation model determines roll deformations and supplies them to a target value determination unit (not shown in more detail here), which uses the determined roll deformations and a contour pattern of the metal strip 1 on the stand discharge side to determine the target values for the profile and flatness control elements in each individual roll stand 3.

Use of the bulge model 12 allows the material flow model 9 and the profile and flatness control implemented in the module 10 (see Figure 1 in each instance) to be adjusted based on the measured data for visible flatness vp. Upper and lower limits can be specified for the visible flatness vp or for the corresponding visible lack of flatness of the strip and these limits can be translated with the aid of the bulge model 12 into limits for the intrinsic flatness ip or intrinsic lack of flatness. The bulge model 12 uses the intrinsic lack of flatness to calculate the bulge pattern of the metal strip 1. The calculated bulge pattern can be used in turn to determine

the visible lack of flatness. Inverse modeling is used for the converse conclusion.

The bulge model 12 is preferably based on the theory of elastic plate deformation. The intrinsic flatness ip is modeled by applying a fictitious strip temperature distribution over the strip width, i.e. in the transverse direction y, resulting in thermal expansion in the longitudinal direction x of the metal strip 1 and at the same time to the length distribution associated with the intrinsic flatness ip.

Let us look now at a strip segment of length a, width b and thickness h as shown in Figure 5. The drawing also shows the longitudinal direction x, transverse direction y and a perpendicular z. Only a strip segment with a length a of a half or whole basic bulge length and with periodic edge conditions at the top and bottom ends of the strip segment is modeled. The edge conditions at the sides of the strip are free edges. The model equations are partial differential equations and the associated edge conditions, which can be solved for example using finite difference methods or finite element methods.

The bulge model 12 can be used directly online as a function of the computing time of the solution algorithm. Alternatively an offline model can be used to generate an online-capable approximation function, which is then used online for the bulge model 12.

To understand the mode of operation of the bulge model 12 better, it first has to be acknowledged that when hot-rolling a metal strip 1 for example, the measured deflections of the metal strip 1, which are due to the bulging of the metal strip

1, are generally significantly larger than the strip thickness h. They are however typically significantly smaller than both the typical wavelength of the bulge behavior and also the strip width b. While the traditional, linear theory of plate deformation only applies when the deflections are less than or equal to approximately 1/5 of the strip thickness h, in the present instance a non-linear description of the plate warp must be used. In addition to the variables shown in Figure 5, which describe the metal strip 1, the elasticity module or e-module for short is also used, with a constant e-module generally being assumed. The non-linear bulge behavior can now be described as follows:

(I) $$\frac{D}{h} \bullet \nabla^4 w(x,y) = \frac{p}{h} + L(w(x,y), \Phi(x,y))$$

Forces operating in the plane of the strip are thereby expressed in the form of a potential Φ, also referred to generally as Airy's stress function. w refers to the vertical displacement of the metal strip 1 while p describes the pressure distribution operating from outside, which acts in the perpendicular z. D is defined by the equation below:

(II) D: $$= \frac{Eh^3}{12(1-\nu^2)}$$

E thereby stands for the e-module and ν stands for the Poisson's ratio of the metal strip 1.

The following also applies for the term $L(w,\Phi)$ from equation (I):

(III) L (w, Φ): $$=\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 \Phi}{\partial y^2}-\frac{\partial^2 w}{\partial y^2}\frac{\partial^2 \Phi}{\partial x^2}-2\frac{\partial^2 w}{\partial x \partial y}\frac{\partial^2 \Phi}{\partial x \partial y}$$

If assumptions are now made in respect of internal stresses and strains due to thermal causes, the following results:

(IV)

$$\frac{1}{E}\bullet\nabla^4\Phi(x,y)+K_x\frac{\partial^2 T(x,y)}{\partial y^2}+K_y\frac{\partial^2 T(x,y)}{\partial x^2}=\left(\frac{\partial^2 w}{\partial x \partial y}\right)^2-\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2}=-\frac{1}{2}L(w(x,y),w(x,y))$$

T thereby refers to the temperature in the metal strip 1 and K_x or K_y the coefficient of thermal expansion in the longitudinal or transverse direction (x or y).

The equations (I) and (IV) form a system of two coupled, non-linear, partial differential equations. If suitable edge conditions are now inserted, for example free edges or periodical edge conditions at the top and bottom ends of a strip segment, the equations (I) and (IV) can be solved numerically in an iterative manner.

The basic concept of the invention can be summarized as follows:

The invention relates to a method and a control device for operating a mill train for metal strip 1, having at least one roll stand 3, with the intrinsic flatness ip of the metal strip 1 being determined at the discharge point of the mill train. To ensure compliance with a required visible flatness vp of the rolled metal strip 1 within predefined limits in a reliable and

sufficiently accurate manner, it is proposed that the visible flatness vp or bulge behavior of the metal strip 1 be determined or preferably be measured at the discharge point of the mill train and be translated into the intrinsic flatness ip of the metal strip 1 using a bulge model 12. The visible flatness can thus be used online with the aid of the bulge model 12 to control the roll stands of the mill train. According to the invention the visible flatness vp can be better regulated preferably online throughout the mill train with the aid of the bulge model 12.

The bulge model 12 is online-capable and establishes a unique relationship between the absolute intrinsic flatness ip of the rolled metal strip 1 and the actual measured visual defects in the metal strip 1, in other words the visible flatness vp. It is possible for the first time to verify, adjust and coordinate a material flow model 9 based on the intrinsic flatness or its corresponding profile and flatness control in respect of the actual measured values.